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LDRD PROJECT TITLE: Multifunctional Integrated Sensors (MFISES)

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ABSTRACT: (250 word limit)

Many emerging IoT applications require sensing of multiple physical and environmental parameters for: completeness of information, measurement validation, unexpected demands, improved performance. For example, a typical outdoor weather station measures temperature, humidity, barometric pressure, light intensity, rainfall, wind speed and direction. Existing sensor technologies do not directly address the demand for cost, size, and power reduction in multi-parameter sensing applications. Industry sensor manufacturers have developed integrated sensor systems for inertial measurements that combine accelerometers, gyroscopes, and magnetometers, but do not address environmental sensing functionality. In existing research literature, a technology gap exists between the functionality of MEMS sensors and the real world applications of the sensors systems.

One method for reducing cost, size, and power consumption and improving the deployability of sensors in multi-parameter applications is to integrate the sensor functions onto a single sensor chip. This thesis will examine two MEMS multi-sensor platforms that I designed, fabricated, and tested that integrated temperature, humidity, pressure, air flow, light intensity, chemical gas, magnetic field, and acceleration functionality. The overall research goal was to meet multi-parameter application performance requirements, maximize the number of functions integrated onto the sensor die, reduce fabrication costs, and stay within the fabrication constraints of the MEMS foundry processes. We used the assessment tool of Quality Function Deployment to design the multi-sensors and select between design options. Using the multi-sensors, I analyzed the cross-sensitivity of each sensor function to other parameters such as the humidity sensor dependence to temperature and pressure using a systematic test method.

The results demonstrated two multi-sensors that reduced the cost and increased the functionality of a sensor system compared to existing literature. Through low power circuit design, we also demonstrated the capability to reduce power consumption for the given functionality versus a system of commercially available components by up to three times. The cross-sensitivity testing provided insight into mechanisms of sensor drift and error. The cross-sensitivity results also enabled the assessment of performance trade-offs due to sensor integration.

INTRODUCTION: (> 500 words with no upper limit)

Consumer and commercial applications that connect real world inputs and outputs to the internet are emerging in applications such as smart buildings, infrastructure monitoring, and surveillance. Examples include buildings that regulate climate settings and lighting depending on room occupancy, networks that monitor vibrations and motion of bridges, and sensors that create virtual fences around military bases. Wireless sensor networks are bridging the gap between the physical world and computation tools for automation, control, and data analysis. Terms for this industry include the Internet of Things (IoT), Internet of Everything, the Trillion Sensor Universe, and the Industrial Internet. Experts and corporations envision that the Internet of Things will drive the sensor industry to volumes of a trillion devices in the next twenty years. Experts also predict that many of the high volume applications have yet to emerge and current paradigms do not exist in real world applications. Future sensor developments that reduce the cost, size, and power and ease the deployment of sensors will enable the realization of the IoT vision.

Many of the emerging IoT applications will require measurements of multiple parameters for: (1) completeness of information, (2) measurement validation, (3) unexpected demands, (4) improved performance. For example, a typical outdoor weather station measures temperature, humidity, barometric pressure, light intensity, rainfall, wind speed and direction. A complete set of weather data enables better forecasting than measuring only temperature and humidity. Many sensor applications monitor only one parameter but use multiple sensors to validate the sensor readings. For example, several cities use magnetic field sensors embedded into parking spaces to detect the presence of a vehicle. The magnetic field sensors are prone to noise from electrical power lines which can cause false event detection. As a solution, the parking sensors often use a proximity or light sensor to verify the magnetic field sensor. Many situations would benefit from extra sensing capabilities. A Swiss Army Knife is an example of a tool with extra built-in functionality for events that the user does not plan for or cannot predict. Smart phones are employing similar concepts to include sensing capabilities such as accelerometers, gyroscopes, magnetometers, pressure, humidity, temperature, and light. The added sensor capabilities that these sensors provide can be used in future applications that engineers did not initially foresee. Finally, multiple sensors can improve system performance as in the case of a magnetometer and accelerometer for compassing. To achieve one degree directional accuracy a magnetometer needs 0.5 degree accuracy to tilt angle which can be measured with an accelerometer with respect to Earth's gravitational field.

Most sensors used in monitoring applications today are microelectromechanical systems (MEMS) that interface with application specific integrated circuits (ASIC). The MEMS sensors are typically fabricated on silicon wafers. One trillion MEMS sensors consisting of two bonded 4 mm² silicon dice would require 260 million 8-inch silicon wafers. At a power consumption of 1 mW, they would consume 1 GW of power. As comparison, a total of 200 million 8-inch wafers were produced for the entire semiconductor industry in 2014 and the Hoover Dam generates 2 GW of electrical power. Current sensor designs are hardly compatible with this vision of the Internet of Things. One method for reducing cost, size,

and power consumption of sensors in multi-parameter applications is to integrate the sensor functions onto a single sensor chip.

The MEMS industry has debated the costs and benefits of integration for many years. Early consumer accelerometers from Analog Devices such as the ADXL05 integrated the proof mass sensing element with the complementary metal oxide semiconductor (CMOS) readout circuitry. Current accelerometers from Bosch and STMicroelectronics split the proof mass and circuitry into separate die. Extensive work from the research groups of Baltes, Gopel, and Wise have investigated the effects of monolithically integrating sensors and CMOS circuitry. They investigated if the drawbacks of integration such as added complexity, reduced process flexibility, and decreased yield outweighed the benefits of increased reliability and reduced parasitics. In a review of microsystems, Lemmerhirt and Wise concluded that future sensor systems would likely be implemented with separate sensor and circuitry dice.

Researchers have not assessed the role of integrating multiple sensor functions into a single package or on a single sensor die as extensively as the question of CMOS integration. Meanwhile in industry, sensor companies have introduced increasingly integrated MEMS devices. The first Analog Devices single-axis accelerometer was introduced in 1993 and then eight years later the first 3-axis accelerometer. Invensense introduced the first combined accelerometer and gyroscope in 2011 and then only two years later Invensense, Bosch and STM had all released combined accelerometer, gyroscope, and magnetometer products. Planned future products include a combined temperature, humidity, pressure, and volatile chemical gas product from Bosch and a pressure, accelerometer, and gyroscope product from Invensense.

DETAILED DESCRIPTION OF EXPERIMENT/METHOD: (> 700 words with no upper limit)

This thesis investigates integration of multiple sensor functions onto a single multi-sensor MEMS die. The overall goal of my research is to reduce the size, power, and cost and increase the functionality of the multi-sensor. I also use the properties of the integrated multi-sensor to improve performance compared to a system of separate sensor components. Finally, I investigate the effects of functional integration on sensor performance and analyze mechanisms of sensor error and drift due to cross-sensitivities.

Change in temperature affects the output of all common MEMS sensors and much of the effort of sensor design is focused on mitigating and compensating for the effect of temperature. The problem of cross-sensitivity extends to other parameters such as humidity, pressure, light, and orientation. The MFISES1 and MFISES2 multi-sensors enable the study of the cross-sensitivity mechanisms and serve as a platform to explore methods of compensation. The integration of the transducers onto a single die means that all the transducers experience nearly the same conditions at the same time points as compared to

a system of multiple discrete components or a co-packaged combo-sensor.

RESULTS: (> 700 words with no upper limit)

The cross-sensitivity testing quantified the relationship between the individual transducer and overall multi-sensor designs to the measurement parameters. The table summarizes the observed cross-sensitivities between transducer and measurement parameter marked in red. I have synthesized all the cross-sensitivity testing to provide a qualitative assessment of the integration level where combining measurement functions is most beneficial to performance. The least integrated level is the circuit board level (C) using two separate sensor die, then the die level (D) where the transducers share the same die, then the most integrated is the transducer level (T) where multiple outputs are integrated into the same physical structure.

Starting at the top of the table, the tested temperature sensors did not clearly show a cross-dependence to any other measurement parameter. For example, the temperature reading of the RTD decreased as air speed increased during the anemometer testing, but this is due to actual temperature change of the multi-sensor. Therefore, cross-sensitivity compensation is not needed for any of the temperature sensors. However, additional sensing capabilities to discern the cause of the temperature change are beneficial. Adding humidity sensing would differentiate if temperature change was due to moisture evaporating or condensing on the sensor. Similarly, the light sensor would indicate if temperature change were due to light radiation, and the air speed sensor would indicate a change in convective heat transfer. Assuming that the temperature, humidity, light, and air speed sensors were exposed to the same conditions, the performance benefits would be achieved at a circuit level integration.

For both humidity sensor designs, inter-digitated silicon combs and metal surface electrodes, temperature affected the sensor offset and sensitivity. Matching the thermal time constant of the humidity sensor with the temperature compensation sensor improves performance and can be done through die level integration. The humidity sensor also showed light and air speed dependencies. We can reduce the light sensitivity with proper shielding of the polymer layer from direct light exposure. The air speed sensitivity corresponded to the temperature change of the sensor die. However, convection from air flow can change the transport mechanism at the polymer-air interface and lead to sensor output change. Sensitivity of the polyimide sensing film to volatile organic compounds often monitored in chemical sensing applications has also been shown. Integrating light, air speed, and chemical sensors at the circuit board level would lead to sensor performance improvements.

The light transducers, both the photodiode and photoresistor, showed cross-sensitivity to temperature only. Transducer integration at the die level would improve performance.

The anemometer had sensitivities to the most number of parameters. The sensitivity mechanism of heat loss to surrounding air depends on the temperature and humidity of the air. We also directly observed sensitivity to orientation relative to gravity. Other research groups have recorded sensitivities to movement, air pressure, and gas composition. Integration of the anemometer and a temperature sensor with similar thermal characteristics at the die level would be most beneficial. Integration with humidity, light, pressure, acceleration, and chemical sensors at the circuit board level would provide additional performance improvement. Inclusion of an accelerometer to determine orientation would be beneficial in applications where the position of the anemometer is unknown or may change. Inclusion of a magnetic field sensor to determine compass direction would also be beneficial for when the position is unknown or in weather applications.

For the piezoresistive pressure transducer, we observed cross-sensitivity due to temperature, light, and air flow. The cross-sensitivity to air flow was greater than the just the change due to temperature or due to the dynamic pressure of the moving air. Temperature sensor integration at the die level would reduce the temperature dependence. For high resolution measurements of pressure, the contribution of dynamic pressure can become significant depending on air speed. The orientation of the pressure sensor with respect to gravity can change the output by 4 ppm. For the capacitive pressure sensor, we observed cross-sensitivities to temperature and humidity. The same performance benefits of air speed and orientation sensing also apply to the capacitive pressure transducer.

For the hall effect magnetic field sensor, we observed cross-sensitivity to temperature and light and for the Lorentz force magnetometer cross-sensitivity only to temperature. To use the magnetic field sensors as compasses, we also need to account for orientation with respect to the horizontal plane which we can measure using an accelerometer. Integrating the magnetic field transducer and accelerometer at the die level enables better axis alignment than at the circuit board level.

All the accelerometer designs had cross-sensitivity to temperature and all the capacitive accelerometers had cross-sensitivity to humidity. The piezoresistive accelerometer also had cross-sensitivity to light. Integrating multi-axis accelerometer capabilities are beneficial for performance at the die level. The accuracy of axis alignment is limited by lithography for die level integration which is more accurate than circuit layout and soldering alignment at the circuit board level.

The MOS chemical transducer was the only sensor that experimentally showed better performance with integration at the transducer level to compensate for temperature and humidity. Light striking the MOS film causes a change in the band gap structure which leads to sensitivity. Other researchers have used anemometer type released resistors to probe the thermal properties of gas species to use as chemical sensors. Combining the thermal data with the MOS chemical sensor could enable better gas identification. Using arrays of chemical gas sensors has also been widely studied as beneficial for gas analysis. Chemical sensor integration with light and chemical sensors and anemometers is beneficial at the circuit level.

Table 6.3: Each transducer is correlated to the other sensing functions to summarize the functional integration level that enables performance benefits. Data derive from experimental measurements using MFISES1, MFISES2, and literature review. The gray cells are correlations between the transducer and the intended measurement function (RTD to temperature, photodiode to light, etc.). The red cells indicate cross-sensitivities that I observed while testing MFISES1 or MFISES2. If the integration of two sensor functions at the circuit board level leads to performance benefits, the cell is marked with a 'C'. If sensor performance improves further with integration at the die level, the cell is marked with a 'D'. If additional improvement occurs at the transducer level, the cell is marked with a 'T'.

Function	Transducer	Beneficial Integration Level									
		Temperature	Humidity	Light	Air speed	Air flow direction	Pressure	Magnetic field	Accel-x,y	Accel-z	Chemical
Temperature	Metal RTD		C	C	C						
	Silicon thermistor		C	C	C						
	Band gap		C	C	C						
	Resonant		C	C	C						
Humidity	Si comb finger	D		C	C						C
	Surface electrode	D		C	C						C
Light	Photodiode	D									
	Photoresistor	D									
Air speed	Anemometer	D	C	C			C	C	C	C	C
Pressure	Piezoresistive	D		C	C						C
	Capacitive	D	C		C						C
Magnetic Field	Hall Effect	D		C					D	D	
	Lorentz force	D							D	D	
Accelerometer	x,y-axis	D	C							D	
	z-axis MFISES1	D	C						D		
	z-axis MFISES2	D	C						D		
	Piezoresistive	D		C					D		
Chemical	SnO2	T	T	C	C		C				C

C Circuit board
 D Sensor die
 T Transducer
 Observed cross-sensitivity

DISCUSSION: (> 700 words with no upper limit)

The motivation to design and build the first generation multi-sensor came from the expansion of wireless sensor networks and the emerging paradigm of the Internet of Things. Many envisioned WSN applications require the measurement of many different parameters to achieve a more complete understanding of what is happening. One example is a weather station that measures temperature, humidity, barometric pressure, light intensity, air speed, and air quality. Another

example is a chemical gas safety monitor mounted to a hard hat that measures chemical gas concentration, vital signs, environmental conditions, movement, and location. Our hypothesis was that a multi-functional sensor could achieve the necessary performance requirements to be useful in some of these applications while reducing the size, power, and cost of the sensor components.

For MFISES1, we investigated an integrated design and fabrication process that would produce a low complexity fabrication process and a multi-sensor with many functions. We balanced the fabrication design and parameters to achieve useful resolution and operating range from all of the sensor functions but not optimal performance for any single function. MFISES1 achieved the integration of ten sensor functions on a 10 x 10 mm silicon die and required only six photolithography steps. Through cost modeling, I estimate that MFISES1 would cost less to fabricate than all but three multi-sensors in literature while achieving more functionality. I designed low power circuits for the sensor biasing and output signal conditioning to show that MFISES1 reduced the total power consumption compared to a system of commercially available discrete components.

For MFISES2, we sought to increase the robustness, decrease the size, and decrease the effect of cross-sensitivities compared to MFISES1. We chose to fabricate MFISES2 in the epi-seal process because of the capability of hermetically sealing moving structures in low vacuum and then surface micromachining environmental sensors on top of the sealed layer. MFISES2 integrated eight sensor functions on a 2 x 2 mm silicon die. We were able to decrease the estimated fabrication cost from \$0.23 per die for MFISES1 to \$0.14 per die for MFISES2. With low power signal conditioning circuits we could also decrease the power consumption of MFISES2 as compared to a comparable system of commercial components.

Using MFISES1 and MFISES2 as test platforms, we investigated the effects of cross-sensitivities on the performance of individual transducers and the overall multi-sensor. MFISES1 and MFISES2 were ideal test platforms because the monolithic integration of sensor functions reduces any gradients or difference in test conditions as compared to a system of multiple discrete components or co-packaged combo-sensors. We correlated the effects of every parameter that MFISES1 could measure to every transducer on MFISES1. Using the correlation of the measurement parameters and transducer outputs, we developed and implemented a cross-sensitivity compensation method. Using MFISES2, we investigated the dynamic effects of environmental changes on the transducer outputs. We used the multi-sensor output of MFISES2 to implement a compensation method to improve sensor stability. The performance of the integrated multi-sensor was better than a system of discrete components in most test cases.

ANTICIPATED IMPACT: (> 700 words with no upper limit; The impact should include description of next step, summary of new proposals deriving from what was learned, follow-on funding, impact on programs, etc.)

Analyzing the existing WSN application literature, I noticed that most applications required completely custom or at least largely customized hardware systems, network communication,

and packaging solutions. In many applications, the project objective was to study bird nesting habits or vineyard micro-climates. Nevertheless, the researchers had to become experts in wireless technology to build their measurement system. As a result, researchers focused most of their time on the tool development and less time on the scientific questions they intended to investigate.

In the scientific community, the development of simple, robust, and general purpose sensor systems would greatly benefit researchers. Experts in wildlife, climate change, structural health, and many other areas could make better progress on their studies if they did not also have to design and build custom measurement systems. Wireless sensor technology platforms exist from companies such as Moog Crossbow, MEMSIC, Libelium, and National Instruments, but I did not see wide-scale adoption of these platforms in the literature that I surveyed. The most commonly platform was the Mica Mote by Dust Networks which is now part of Linear Technology.

I think the biggest challenge for present sensor node technology is reducing power consumption and extending battery life. The limiting factor for communication range, data rates, sensor functionality, size, and system autonomy are all related to the amount of stored energy in the sensor node and the power consumption of the device. Energy scavenging as a method to power sensor nodes or extend battery life is only a practical solution in direct sunlight. Solar cells can directly power sensor nodes in outdoor applications but are less useful indoors. Scavenging energy from sources such as vibrations, temperature gradients, and radio frequencies results in very low efficiencies and overall power output capabilities. Since generating electrical power is a large technical obstacle, then reducing power consumption is the alternative solution. Existing technology such as tire pressure monitoring systems from Freescale consume about 100 mW of power and can operate for 3-7 years before requiring replacement. These systems represent a near-term power consumption goal for sensor nodes.

Further in the future, I think that reducing the cost of the sensor systems would enable many new applications. If the cost becomes low enough for disposable sensor systems to be economically viable, then many new use cases emerge. For example, integrating chemical sensors into food packaging to test for spoilage and integrating moisture sensors into bandages to monitor wound conditions. Sensors could monitor temperature and humidity conditions for medicine storage. Accelerometers could track the shipping and handling of electronics to ensure they were not dropped or crushed. Obviously, the sensor system is only one part of the technology stack. Communication and data analysis also require further advancements to enable pervasive disposable sensors. Nevertheless, we can imagine radically new technologies that would effect our everyday lives, if the cost of sensor systems dramatically decreases.

CONCLUSION: (500 word limit)

The Internet of Things is driving new sensor applications into areas like environmental, condition, and structural health monitoring. The MEMS industry must develop new methods to reduce the size, power, and cost of sensors given the increasing demand. Most of the monitoring applications require the sensing system to monitor multiple parameters. There are different

methods to make multiple measurements: multiple individual sensors, combo-sensors, multi-sensors, and fused sensors. However, a thorough investigation of the advantages and disadvantages of the levels of sensor integration has not been shown yet.

Commercially available combo-sensors and multi-sensors are experiencing rapid development with the focus on inertial measurement units that combine accelerometers, gyroscopes, and magnetometers. Academic researchers have explored many designs for combo-sensor, multi-sensor, and fused sensor systems. Nevertheless, a disparity exists between the functional requirements of current and emerging wireless sensor network applications and the current sensor systems.

This thesis explores the design, fabrication, and testing of multi-sensors with the goal of operating in multiple categories of applications. The results demonstrated two multi-sensors that reduced the cost and increased the functionality of a sensor system compared to existing literature. Through low power circuit design, we also demonstrated the capability to reduce power consumption for the given functionality versus a system of commercially available components by up to three times. The cross-sensitivity testing provided insight into mechanisms of sensor drift and error. The cross-sensitivity results also enabled the assessment of performance trade-offs due to sensor integration.

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